# HOLOCINEMATOGRAPHY FOR STUDIES OF TURBULENT MULTIPHASE FLOW

by

G. M. Faeth, G. A. Ruff and L. P. Bernal

College of Engineering

DEPARTMENT OF AEROSPACE ENGINEERING

The University of Michigan
Ann Arbor, Michigan 48109-2140

2

GDL/GMF-90-02

# HOLOCINEMATOGRAPHY FOR STUDIES OF TURBULENT MULTIPHASE FLOW

by

G. M. Faeth, G. A. Ruff and L. P. Bernal

30 January 1990

U. S. Army Research Office
Grant No. DAAL03-89-G-0004

Department of Aerospace Engineering
The University of Michigan



**Approved for Public Release; Distribution Unlimited**

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

# REPORT DOCUMENTATION PAGE

| | |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>Unclassified | 1b. RESTRICTIVE MARKINGS |
| 2a. SECURITY CLASSIFICATION AUTHORITY | 3 DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release;<br>distribution unlimited. |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)<br>Report No. GDL/GMF-90-02 | 5. MONITORING ORGANIZATION REPORT NUMBER(S) |
| 6a. NAME OF PERFORMING ORGANIZATION<br>Dept. of Aerospace Engineering<br>The University of Michigan<br>6b. OFFICE SYMBOL (If applicable) | 7a. NAME OF MONITORING ORGANIZATION<br>U. S. Army Research Office |
| 6c. ADDRESS (City, State, and ZIP Code)<br>217 Aerospace Engineering Building<br>Ann Arbor, MI 48109-2140 | 7b. ADDRESS (City, State, and ZIP Code)<br>P. O. Box 12211<br>Research Triangle Park, NC 27709-2211 |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION<br>U. S. Army Research Office<br>8b. OFFICE SYMBOL (If applicable) | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>DAAL03-89-G-0004 |
| 8c. ADDRESS (City, State, and ZIP Code)<br>P. O. Box 12211<br>Research Triangle Park, NC 27709-2211 | 10. SOURCE OF FUNDING NUMBERS<br>PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO. |

11. TITLE (Include Security Classification)

Holocinematography for Studies of Turbulent Multiphase Flow (U)

12. PERSONAL AUTHOR(S) G. M. Faeth, G. A. Ruff and L. P. Bernal

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| Final | FROM 12/15/88 TO 12/15/89 | 15 January 1990 | 23 + v pp. |

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |
|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | Holography |
| | | | Flow Visualization |
| | | | Multiphase Flow |

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The development of a high-speed holocinematography system for three-dimensional time-dependent measurements of the dynamics of dispersed flows is described. An on-line system based on a copper-vapor laser was assembled and used to obtain holocinematogram film strips of a particle-containing flow field. The present system can operate at framing rates up to 6000 holograms per second, yielding film strips up to 70 holograms long with a field of view having a diameter of 35 mm and a length of 120 mm. Extension to an off-axis configuration, for higher resolution, also appears to be feasible. Either configuration provides unprecedented capabilities for studying laminar and turbulent single or multiphase flow phenomena that are not accessible using existing methods.

| | |
|---|---|
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>Unclassified |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>David M. Mann | 22b. TELEPHONE (Include Area Code) (919) 549-0641 / 22c. OFFICE SYMBOL |

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

## Table of Contents

## List of Tables

## List of Figures

## 1. Statement of Problem

Turbulent dispersed flows (e.g., drop, particle- or bubble-containing flows) have numerous practical applications to combustion, heat and mass transfer, and fluid-dynamic systems. Motivated by these applications, there has been significant progress in gaining a better understanding, as well as capabilities for modeling, the mean properties of these flows (Faeth, 1987). Nevertheless, both computational and experimental limitations have prevented systematic study of many important unit processes of dispersed flows, for example: distortion of drops and bubbles, breakup processes, collision processes, turbulent dispersion, effects of turbulence on interphase transport, and the modification of turbulence by the motion of a dispersed phase, among others. The objective of the present investigation was to initiate development of holocinematography systems that provide new experimental capabilities for addressing problems of this type. In particular, holocinematography yields three-dimensional time-dependent images of dispersed flows that can be interrogated at leisure, much like the output of three-dimensional time-dependent numerical simulations of dispersed flows. The advantage of holocinematography, however, is that it can be applied to practical high-speed and large-scale flows that will not be feasible for treatment by numerical simulations for some time to come.

Analogous to motion pictures being an outgrowth of still photography, holocinematography is an outgrowth of holography. Holography was invented by Gabor (1948), of Imperial College, based on an in-line configuration that could be used with an incoherent illumination source. Holography, however, attracted little attention as a practical instrument system until continuous-wave lasers were developed to provide sources of coherent light. Shortly thereafter, Leith and Upatnieks (1964) of the University of Michigan, developed off-axis holography which was capable of providing sharp three-dimensional images of solid objects. In the following years, double-pulse holographs, low framing rate motion-picture holographs (holocinematography), and other developments followed rapidly (Lehmann, 1970; Lee and Kim, 1986).

Past use of holography for studies of multiphase flows has been primarily limited to double-pulse holography, which provides the short exposure times, ca. 20 ns, needed to stop and resolve small fast-moving objects. An arrangement used in this laboratory for studies of the near-injector (dense-spray) region of pressure-atomized sprays is illustrated in Fig. 1 (Ruff et al., 1989; Ruff and Faeth, 1990). This is an off-axis arrangement based on the Spectron Development Laboratories Model HTRC-5000 system but substantially modified to provide holograms of dense sprays. The system has a ruby laser light source that can be double-pulsed, yielding two holograms on the same film. Such double-pulsed holograms can be reconstructed to show the object field at two instants of time. This provides a means of measuring the velocities of objects at a particular instant over a three-dimensional field; however, the flow cannot be time resolved.

A hologram carries light amplitude and phase information that yields a three-dimensional image of the object upon reconstruction. This image can be projected indefinitely; therefore, it can be scanned by any convenient technique to measure flow properties. Furthermore, although holography is a lensless system with a very large depth of field, the reconstruction system can independently involve high magnification. This provides capabilities for resolving the position and size of small objects over large observation volumes that makes holography particularly suited for studies of multiphase flows.

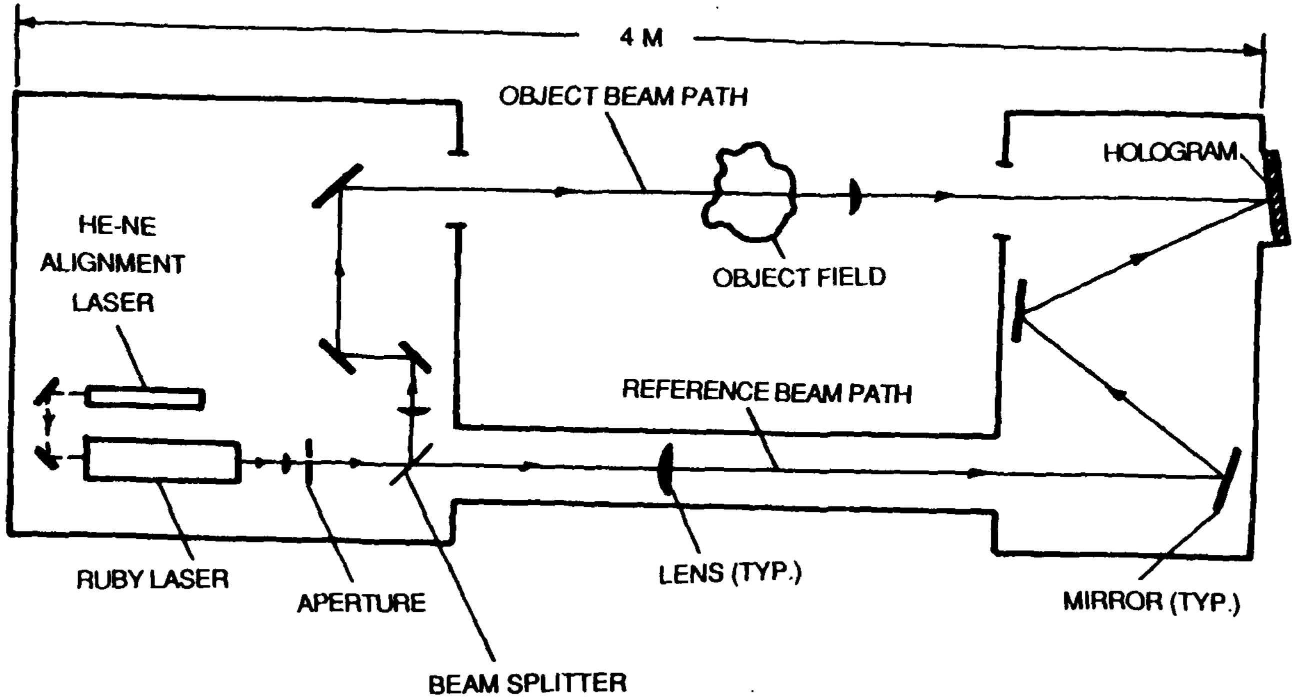


Figure 1  Sketch of off-axis hologram recording arrangement.

The hologram reconstruction system used in this laboratory is illustrated in Fig. 2 (Ruff et al., 1989; Ruff and Faeth, 1990). The beam from a 15 mW cw HeNe laser is expanded and then passed through the developed holographic plate. The off-axis configuration illustrated in Fig. 1 provides a real magnified image of the spray in the region in front of the hologram. The properties of this region are observed with a video camera having a high magnification and a short depth of field. This allows small objects (drops) to be resolved, and also reduces problems of optical noise due to out-of-focus drops (much like a microscope allows observation of narrow planes in a complex object field). Computer-controlled x-y traversing of the hologram and z traversing of the video camera allow the region crossed by the object beam to be studied, using a Gould FD5000 Image Processing System. When analyzed in this manner, the data storage capabilities of a single hologram is quite impressive, e.g., a typical hologram contains $10^{12}$ - $10^{14}$ bytes of information (or spatial locations) upon reconstruction.

Clearly, extending holography to holocinematography provides unprecedented potential for resolving three-dimensional time-dependent events. For example, current supercomputers can handle ca. $10^6$ spatial locations in a time-dependent numerical simulation of fluid dynamic phenomena. Thus, even with computer capabilities growing at historical rates, $10^2$ per decade, it appears that holographic methods will have the capability to challenge numerical simulations for some time to come — aside from the obvious advantage that holography allows observations of actual physical events without questionable approximations.

This potential has always been evident to those working with holography systems. Thus, low framing rate motion picture holography, or holocinematography, was demonstrated shortly after the invention of off-axis holography by Leith and Upatnieks (1964), see Lehmann (1970). Occasional application of holocinematography has been reported in the intervening years, based on both pulsed and continuous wave (cw) lasers (Trolinger, 1975; Lee and Kim, 1986). Present interests for treating multiphase flows requires framing rates greater than 100 holograms per second, thus the following discussion will be limited to this high framing rate regimes.

Ebeling and Lauterhorn (1977) developed a high-speed holocinematography system for studies of laser-induced cavitation in liquids. This system was based on a Q-switched ruby laser which produced off-axis holograms at rates of 20000 holograms per second. Q-switching, however, was limited to a single pumping period of the laser, so that the number of holograms was limited to a total of 8. Thus, while this system had good light energy per pulse, ca. 2 mJ, and short pulse durations to stop the motion of fast objects, ca. 30 ns, the limited total number of pulses did not provide an attractive approach to record physical events.

Long term temporal tracking of events has been pursued using cw lasers. Weinstein et al. (1985) have developed a system based on mechanically chopping cw lasers. However, this system is most effective for slow-moving objects. In particular, the duration of each mechanically chopped pulse is relatively long so that fast moving objects tend to smear out their image and cannot be resolved if they are small. Even with cw laser powers of 20-100 W, the time required to deposit enough light energy to expose the film remains an impediment for studying fast events involving small objects (Weinstein et al., 1985).

The development of metal vapor lasers has the potential for removing past limitations of holocinematography. These lasers have fast pulsing rates ca. 10 kHz;

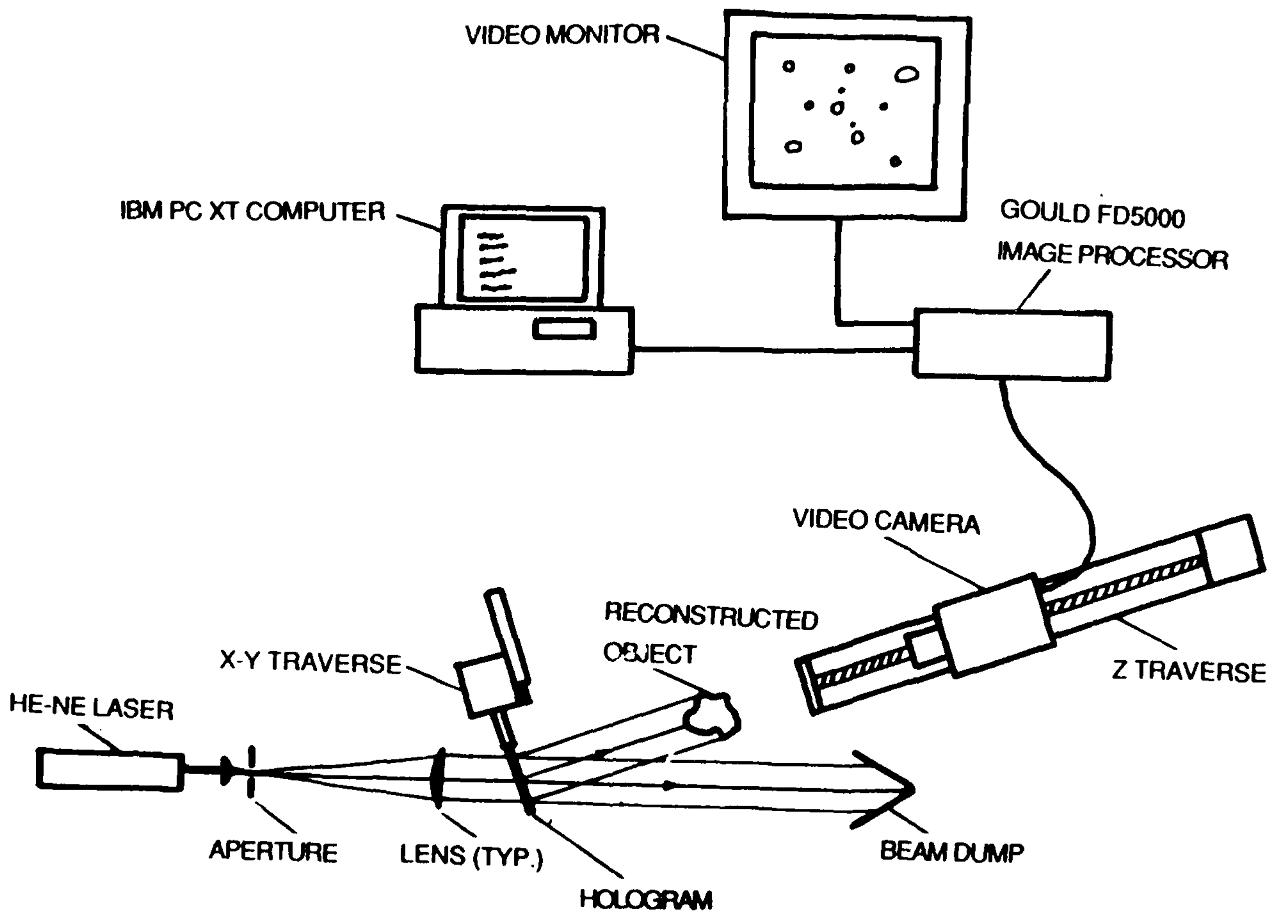


Figure 2 Sketch of off-axis hologram reconstruction arrangement.

short pulse durations, ca. 20-30 ns; large optical energy deposition per pulse, ca. 2 mJ; and can be pulsed indefinitely for long temporal records. Thus, they are promising for use in holocinematography systems to record multiphase-flow events. Whether laser coherence is adequate for holography is always an issue, however, one copper-vapor laser manufacturer demonstrated successful holograms with good reconstructions being achieved for distances up to 40 mm along the optical axis (Picarello, 1988). In view of this finding, the objective of the present investigation was to study the feasibility of holocinematography at framing rates on the order of $10^3$-$10^4$ holograms per second, using a copper-vapor laser; and to demonstrate the operation of the system for a simple particle-laded multiphase flow, involving particles colliding with a plane surface.

The development and results of the holocinematography system are described in the next chapter, considering apparatus, results and conclusions in turn. Subsequent chapters summarize publications and personnel of the investigation. Additional information concerning the study can be found in Ruff et al. (1990), which appears in the Appendix.

## 2. Summary of Most Important Results

### 2.1 Apparatus Development

Holocinematography System. Components acquired for the holocinematography systems are summarized in Table 1. These items are sufficient for assembling both off-axis and on-line arrangements as illustrated in Figs. 3 and 4, respectively. Aside from optical components, the main elements of the system are: a 20W copper-vapor laser to drive the system (Metalaser Technologies Model 2051); a function generator to control pulsing of the laser (Hewlett-Packard Model 3314A); and a continuous-writing, or nonframing, drum camera to record hologram film strips (Cordon Model 351).

The off-axis holocinematography system, Fig. 3, has a backscatter-like arrangement so that laser, optics and camera can be rigidly mounted to the same optical table to minimize alignment problems. Copper-vapor lasers emit power at two wavelengths (roughly 60 percent at 510.6 nm and 40 percent power at 578.2 nm): the weaker yellow line is separated and dumped to provide monochromatic coherent light needed for holography. The short axial coherence lengths of copper-vapor lasers (ca. 120 mm for the present laser) pose a problem, since the optical path length of the object and reference beams must be closely matched (within a few cm as opposed to the less stringent requirements for ruby lasers which have axial coherence lengths of ca. 1 m). This is accomplished by using the same lenses in each path and providing a set of path-matching mirrors in the reference-beam path which can be accurately translated to adjust the optical path length. A beam expander (contractor) lens system allows adjustment of object beam intensities and the field of view, which is often needed for measurements in dense dispersed flows (Ruff et al., 1989; Ruff and Faeth, 1990). Focussing lenses in each path then resize the beams to fit the 35 mm format of the nonframing camera. This camera provides the stable platform needed for high-resolution holography, even though the film is moving.

While the off-axis configuration has the greatest potential for practical measurements, due to its higher resolution, present work was limited to the on-line configuration illustrated in Fig. 4. The main advantages of the on-line system is simpler alignment of the recording optics and less restrictive axial and transverse coherence requirements (Trolinger, 1975). In this case, both object and reference

**Table 1. Summary of Equipment**

| Quantity | Description |
|---|---|
| <u>Metalaser Technologies, Inc.</u>: | |
| 1 | Model MLT/20, 20 W copper-vapor laser |
| 1 | Model 20/UR, unstable resonator optics |
| 1 | Model DFS-1, dichroic beamsplitter |
| <u>Cordin</u>: | |
| 1 | Dynaflex Model 351 continuous writing streak camera |
| <u>Coherent, Inc.</u>: | |
| 1 | INNOVA 70-2, 2 W (all lines) argon-ion laser |
| <u>Hewlett-Packard Co.</u>: | |
| 1 | Model 3314A frequency, function and waveform synthesizer |
| <u>Newport Corp.</u>: | |
| 1 | Model RS-410-12, 4 × 10 ft. honeycomb table top, 12 in. thick, with Model XL4A-28 leg system. |
| 3 | Model KPX187 planoconvex lens, 50.8 mm dia. × 100 mm focal length |
| 2 | Model KPX199 planoconvex lens, 50.8 mm dia. × 200 mm focal length |
| 1 | Model LP-05-XY two-axis translator |
| 2 | Model SP-4 support post |
| 2 | Model VPH-4 post holder |
| 1 | Model 20B20BS.1 beamsplitter |
| 6 | Model 20D20BD.1 mirrors |
| 2 | Model 100 magnetic base |
| 10 | Model 150 magnetic base |
| 3 | Model 600A-2 optical mount |
| 4 | Model 740 lens positioner |

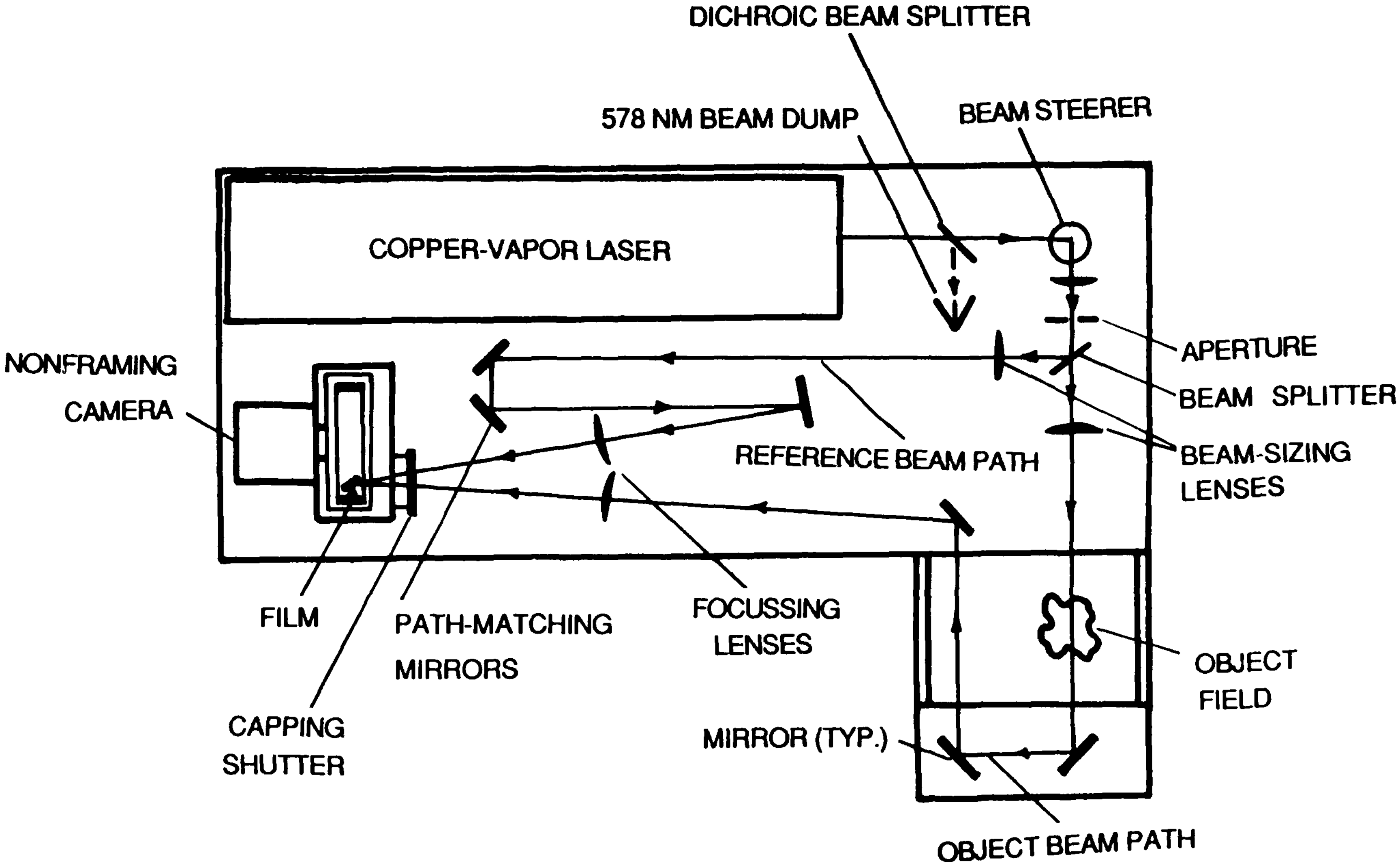


Figure 3 Sketch of off-axis holocinematography recording arrangement.

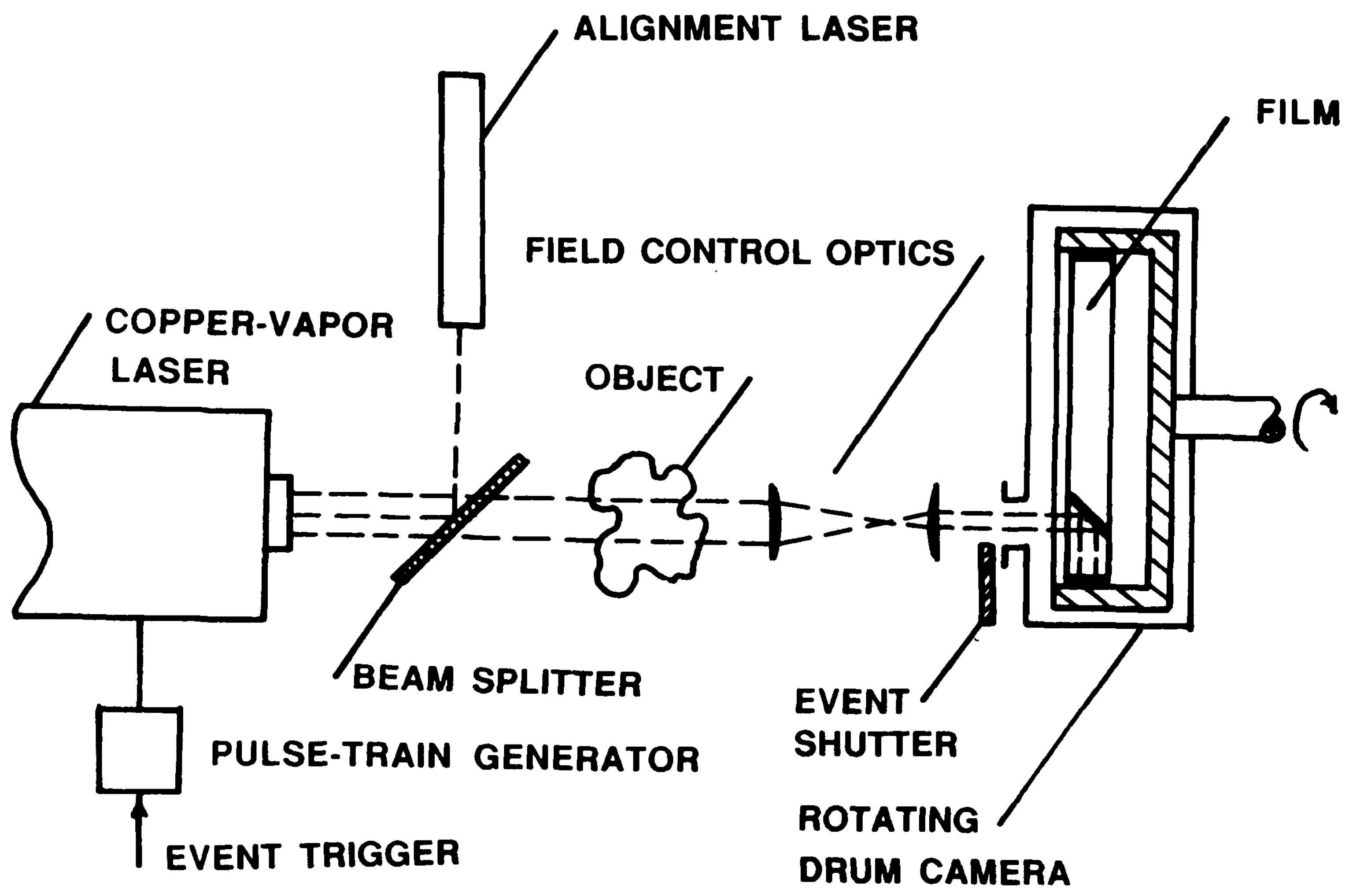


Figure 4 Sketch of in-line holocinematography recording arrangement.

beams travel the same path through the object field, the reference beam simply being that portion of the laser beam which is unaffected by the object field. The field control optics are similar to the off-axis arrangement, except that no optical path length adjustment is required for the on-line arrangement.

To operate the system, the copper-vapor laser must be brought up to operating conditions at a conventional pulse rate (6-10 kHz). Control then shifts to the function generator which produces the desired number and frequency of laser pulses which just exposes the entire length of film in the nonframing drum camera (depending on the image format, the 272 mm diameter drum can accommodate film strips with 35-70 hologram images). The camera can operate with drum speeds up to 133 m/s, its speed is adjusted to match the pulse rate so that images do not overlap or have excessive space between them. This can be done accurately since the camera generates four timing signals per revolution while the large drum inertia prevents short-term speed variations. The capping shutter on the camera is synchronized with the laser burst so that the film is not double-exposed or fogged by background light.

The laser deposits roughly 2 mJ of optical energy per pulse at 510.6 nm, with a pulse duration of 20-30 ns. This yields a maximum optical energy deposition on 35 mm film (with normal full-frame format) of ca. 1 mJ/cm$^2$, which is roughly three orders of magnitude higher than levels required for minimum exposure (using AGFA 10E75HD NAH, 35 mm format). This provided excellent exposure margins for absorption of the laser beam by the object field. Thus, only a portion of the laser beam was actually used for the holograms, in order to maintain relatively uniform contrast over the object field. The short pulse duration implies that an object moving at a speed of 25 m/s, which is typical of drops in sprays in the atomization breakup regime, will move less than 1 $\mu$m during the laser pulse, providing good resolution of small objects.

The present in-line holograms generally satisfied the far-field requirement for small objects (Hariharan, 1983), e.g., $z \gg d^2/\lambda$, where d is the object diameter, $\lambda$ is the laser wavelength, and z is the distance from the particle to the holographic recording medium. Therefore, the hologram is formed by the interference of the far-field (Fraunhofer) diffraction pattern of the particle and the directly transmitted light, resulting in a Fraunhofer hologram. The holograms were reconstructed and images processed using the basic arrangement illustrated in Fig. 2, see Lehmann (1970).

Coherence Lengths. The axial coherence length of the copper-vapor laser was measured since this defines field sizes for adequate hologram reconstructions. These measurements were carried out using a Michelson interferometer arrangement as described by Lehmann (1970). The measurements yielded an axial coherence length of 120 mm for the present laser, which is sufficient for many applications involving multiphase flows.

Test Flow. A relatively simple flow was considered to test the feasibility of holocinematography. This involved a stream of round glass beads (approximately 500 $\mu$m in diameter) falling from a delivery chute and impacting on a flat horizontal metal surface. Variations in the initial velocity, the shape of the glass beads and the smoothness of the impact surface affect the direction of motion of each rebounding bead. Measurements involved the trajectories of several beads, as they approached and rebounded from the surface, with all data obtained from a single hologram film strip.

The object field also included two pins (500 μm diameter and 3 mm apart), perpendicular to the surface, which were used as position reference points.

### 2.2 Experimental Results

Some typical results from the operation of the holocinematography system are illustrated in Fig. 5. These results were obtained with the copper-vapor laser pulsed at 0.82 ms intervals (1220 holograms per second) with the drum camera rotational speed set to 30 revolutions per second, yielding 35 nonoverlapping holograms on the film strip. Three consecutive in-line holograms taken from the film strip are illustrated in Fig. 5. Large objects in the object field of an in-line hologram have an appearance somewhat like shadowgraphs so that the fixed reference pins and several moving glass beads can be seen in the hologram (note the change of position of the highlighted and other beads relative to the fixed pins). On-line holograms are different than shadowgraphs, however, since the outline of each object actually involves a fringe pattern related to its size and axial location.

Photographs of reconstructed images of the highlighted bead from the first and third holograms are also illustrated in Fig. 5. These photographs were obtained from the video monitor of the image analysis system (Fig. 2) and have a total field of view of 1.9 × 2.9 mm within the object field (the highlighted bead was actually 480 μm in diameter). The reconstructed image of the glass bead is a white circular outline on a relatively dark background since a Fraunhofer hologram was obtained, i.e, the image is formed by the diffraction pattern from the periphery of the bead. The bright spot at the center of the circle is caused by the focussing effect of the transparent glass bead. By seeking sharp images of the circular outline and the center spot, the axial position of the bead can be determined with reasonable accuracy.

Reconstructed holograms from the entire film strip were processed to obtain three-dimensional, time-dependent trajectories of two glass beads. These trajectories are illustrated in Fig. 6. The depth of the volume recorded, evidenced by the distance between beads in the y direction, is seen to be at least 6 mm. This just represents the width of the present flow, the axial coherence measurements indicate that depths up to 120 mm are obtainable, as noted earlier. Coupled with a high magnification for the video camera used to view the reconstructed image, this effectively eliminates depth-of-field limitations encountered when investigating particle-containing fields using conventional imaging techniques.

An obvious limitation of the on-line configuration is that the reconstructed image is only an outline of the object. This tends to limit spatial resolution and requires good optical signal-to-noise ratios in order to avoid gaps in the outline of objects. Off-axis holograms eliminate these deficiencies since a sharp shadowgraph of in-focus objects is obtained from the reconstruction (Ruff et al., 1989). Thus, current efforts are devoted to assembling and testing an off-axis holocinematography arrangement, along the lines of Fig. 3.

### 2.3 Conclusions

The objective of this investigation was to assemble equipment and study the feasibility of high framing rate holocinematography based on copper-vapor lasers. The main conclusions of the study are as follows:

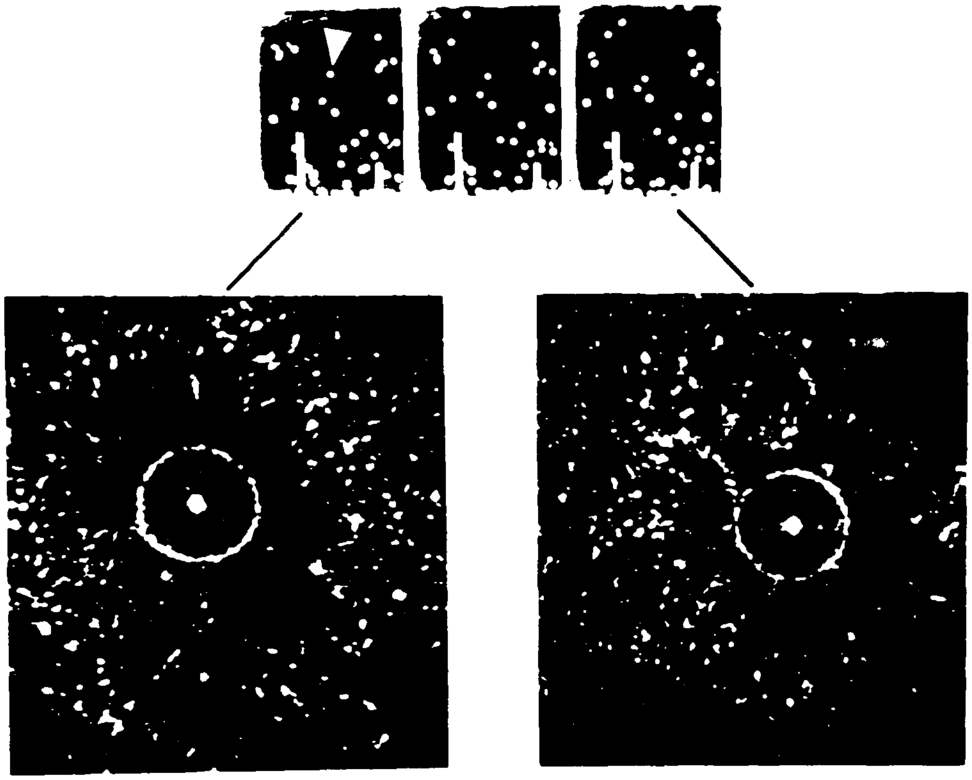

Figure 5 Film strips of in-line holocinematograms and corresponding reconstructed images.

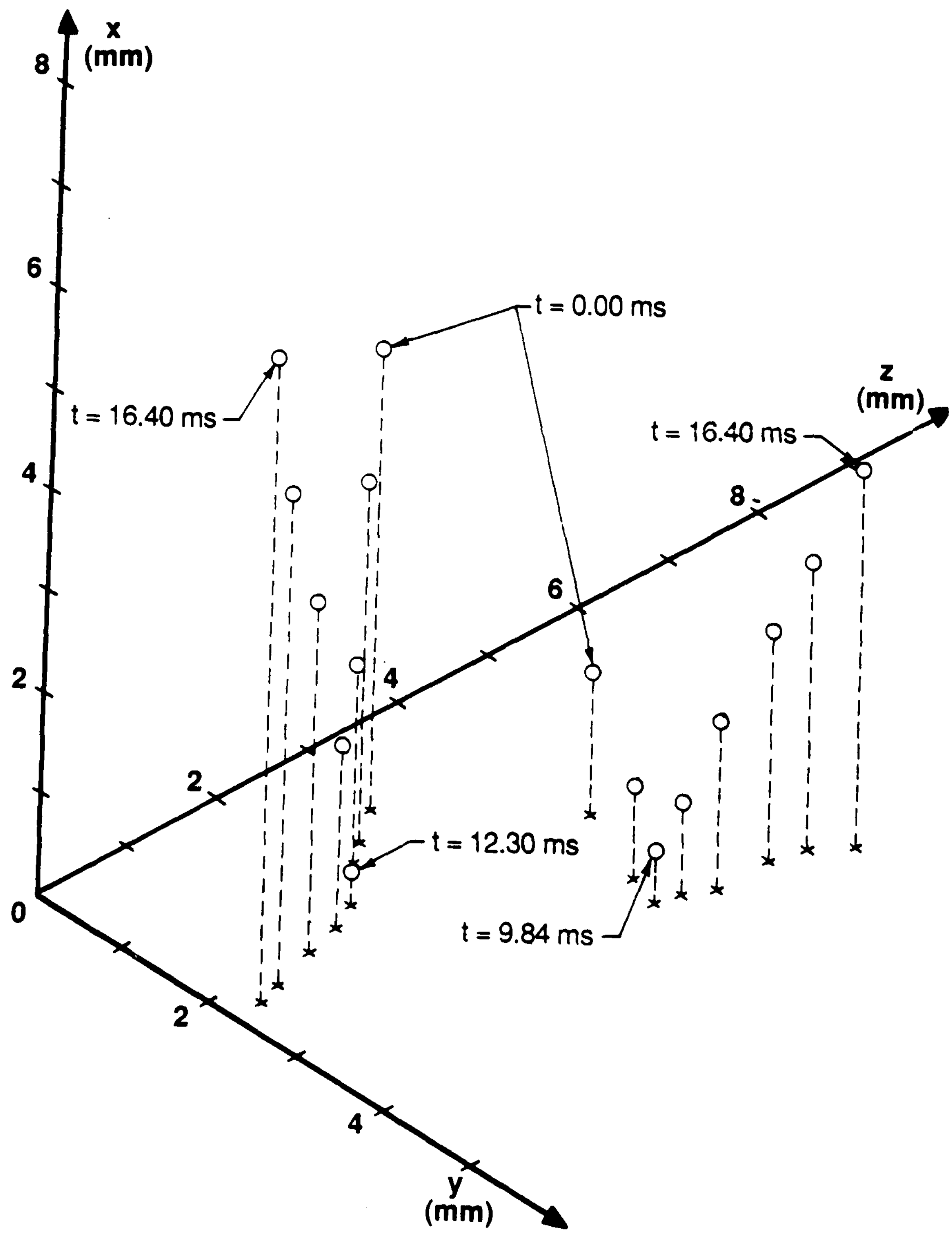


Figure 6 Three-dimensional time-dependent tracks of two glass beads obtained from the holocinematograms of Fig. 5.

1. The axial coherence length of the present copper-vapor laser was 120 mm, thus, use of these lasers for pulsed holograms or holocinematography with reasonable object volumes is feasible.

2. An on-line holocinematography arrangement yielded good hologram film strips (35 frames long) at a framing rate of 1220 holograms per second. The present arrangement can provide framing rates up to 10000 holograms per second (70 frames long) over a reasonably large object field (ca. 35 mm diameter $\times$ 120 mm long) which is adequate for studies of many dispersed-phase processes in multiphase flows. Available data on a hologram film strip of this type corresponds to $70 \times 10^{12}$-$10^{14}$ bytes upon reconstruction. Thus, the capabilities of holocinematography to resolve practical three-dimensional time-dependent dispersed flows are very attractive.

3. On-line holocinematography involves a relatively simple optical configuration with minimal problems concerning coherence lengths of the laser source. However, off-axis holography has innately higher resolution and capabilities of reducing effects of optical noise, and should receive attention in order to realize the full capabilities of holocinematography.

## 3. List of Publications

Ruff, G. A. Bernal, L. P. and Faeth, G. M., "High-Speed In-Line Holocinematography for Dispersed-Phase Dynamics" *Applied Optics*, submitted, 1990.

## 4. List of Participating Scientific Personnel

G. M. Faeth, Principal Investigator, Professor, The University of Michigan

L. P. Bernal, Assistant Professor, The University of Michigan

G. A. Ruff, Graduate Assistant, The University of Michigan, Ph.D., June 1990

P.-K. Wu, Graduate Assistant, The University of Michigan.

## References


Ebeling, K. J. and Lauterhorn, W. (1977) High speed holocinematography using spatial multiplexing for image separation. *Optics Comm.* 21, pp. 67-71.

Faeth, G. M. (1987) Mixing, transport and combustion in sprays. *Prog. Energy Combust. Sci.* 13, pp. 293-345.

Gabor, D. (1948) A new microscope principle. *Nature* 161, pp. 777-778.

Hariharan, P. (1983) *Optical Holography: Principles, Techniques and Applications.* Cambridge University Press, New York, p. 175.

Lee, Y. J. and Kim, J. H. (1986) A review of holography applications in multiphase flow visualization study. *J. Fluids Engrg.* 208, pp. 279-288.

Lehmann, M. (1970) *Holography Technique and Practice.* Focal Press Limited, London, pp. 75-84.

Leith, E. N. and Upatnieks, J. (1964) Wavefront reconstruction with diffused illumination and three-dimensional objects. *J. Opt. Soc. Am.* 54, pp. 1295-1301.

Picarello, S. (1988), Metalaser Technologies, Inc., personal communication.

Ruff, G. A. and Faeth, G. M. (1990) Continuous-phase properties of the near-injector region of pressure-atomized sprays. AIAA Paper No. 90-0464.

Ruff, G. A., Bernal, L. P. and Faeth, G. M. (1989) Structure of the near-injector region of non-evaporating pressure-atomized sprays. AIAA Paper No. 89-0050; also, *J. Prop. Power*, in press.

Ruff, G. A., Bernal, L. P. and Faeth, G. M. (1990) High-speed in-line holocinematography for dispersed-phase dynamics. *Appl. Optics*, submitted.

Trolinger, J. D. (1975) Particle field holography. *Opt. Engrg.* 14, p. 383-392.

Weinstein, L. M., Beeler, G. B.and Linderman, A. M. (1985) High-speed holocinematographic velocimeter for studying flow control physics. AIAA Paper No. 85-0526.

Appendix: "High-Speed In-Line Holocinematography

for Dispersed-Phase Dynamics"

G. A. Ruff, L. P. Bernal and G. M. Faeth

*Applied Optics*, submitted, 1990

# High-Speed In-Line Holocinematography for Dispersed-Phase Dynamics

by

G. A. Ruff, L. P. Bernal and G. M. Faeth
The University of Michigan
Ann Arbor, Michigan 48109-2140

A holocinematography system, where a series of spatially multiplexed holograms are recorded in rapid (up to 10 kHz) succession, is described in this letter. The potential of holocinematography to provide three-dimensional time-dependent information concerning fluid-flow phenomena has been recognized for some time.[1,2] In particular, relatively high framing rate systems have been developed that are suitable for studying dispersed-phase dynamics in multiphase flows.[3,4] Ebeling and Lauterhorn[3] reported a system based on a Q-switched ruby laser which produced off-axis holograms of cavitation bubbles at 20 kHz. However, Q-switching was limited to a single pumping period of the laser so that only eight holograms could be obtained on each record, reducing the potential of the system for recording physical events. Weinstein et al.[4] pursued long-term temporal tracking of events by mechanically chopping cw lasers. Unfortunately, a relatively long time is required to deposit enough light energy to produce each hologram record with currently available cw lasers; therefore, this approach is limited to relatively low velocities if the test objects are small. Thus, present work sought to remove past limitations concerning pulse rates and record lengths by considering a holocinematography system based on a copper-vapor laser. Operation of the system was demonstrated by recording and reconstructing hologram images of an event representative of multiphase flows; namely, three-dimensional time-dependent tracks of glass beads striking a flat surface.

An in-line holocinematography configuration, illustrated in Fig. 1, was investigated because of ease of optical alignment and less restrictive axial and transverse laser coherence length requirements.[5] When recording holograms of small-diameter particles, the distance from the particles to the recording medium generally satisfies the far-field requirement,[6] i.e., $z >> d^2/\lambda$, where d is the particle diameter, $\lambda$ is the wavelength of the incident radiation, and z is the distance from the particles to the hologram recording medium. Therefore, the holograms are formed by the interference of the far-field (Fraunhofer) diffraction pattern of the particle and the directly transmitted light, yielding Fraunhofer holograms.

The illuminating beam of the holographic recording system was produced by a pulsed 20 W copper-vapor laser (Metalaser Technologies Model 2051). This laser requires a continuous pulse-rate of 6-10 kHz for proper operation, however, slower pulse rates, and even single laser pulses, can be obtained for short periods (5-10s) without the plasma tube cooling below temperatures required for lasing. At 8 kHz, the energy per pulse is approximately 2 mJ with pulse widths less than 30 ns which provides good margins for exposing the hologram film and stopping the motion of small high-speed objects. Unstable resonator optics within the laser cavity produce a nearly collimated 32 mm diameter beam. A dichroic mirror was used to remove the yellow (578.2 nm) line, allowing only the green (510.6 nm) line, which contains roughly 60 percent of the average power, to reach the test area. The pulse rate of the copper-vapor laser was controlled by a function generator (Hewlett-Packard Model 3314A) capable of both free-run and gated modes of operation.

After crossing the test area, the laser beam passed through field-control optics that provided a 2X magnification of the object volume and increased the diameter of the uniform region of the illuminating beam. The holograms were recorded using a nonframing drum camera (Cordin Model 351) that rotated the film (AGFA 10E75HD NAH, 35 mm format) at speeds up to 156 revolutions per second (approximately 133 m/s). A first-surface mirror and field stop directed and formatted the beam to place the hologram record on the film. The film was loaded onto the inner diameter (272 mm diameter) of the camera drum . An event shutter, which remained open for one revolution of the drum, prevented overwriting the film.

The test object consisted of nearly spherical glass beads (approximately 500 μm in diameter) falling from a delivery chute and bouncing off a flat metal surface. Variations of the initial velocity and shape of the beads, and the smoothness of the impact surface, affected the trajectories of the beads as they approached and rebounded from the surface. Two pins (500 μm in diameter) were mounted perpendicular to the flat surface, 3 mm apart, to provide position reference points.

A standard in-line reconstruction system,[7] using a 15 mW HeNe cw laser operating at 632.8 nm, was used to reconstruct the images of the glass beads. For present purposes, the hologram film strip was mounted in a metal frame holder and advanced manually frame-by-frame. The images were viewed using a video camera and observed on a monitor. Computer-controlled x-y traversing of the hologram and z traversing of the video camera, allowed the position of each bead to be determined. Production of the data was facilitated by an image-processing system (Gould FD 5000) that contained features to smooth the digital image, to reduce effects of laser speckle and optical noise, and to locate and size individual objects.

Present holocamera operating conditions were selected so that reasonable path lengths of the beads, before and after striking the wall, could be tracked; thus, they don't represent operating limits of the system. This involved pulsing the copper-vapor laser at 1.22 kHz, to yield 35 nonoverlapping holograms on the film strip with the drum camera rotating at 30 revolutions per second. Three consecutive in-line holograms taken from a typical film strip are illustrated in Fig. 2. The reference pins are visible in each hologram and the motion of the beads between exposures is clearly evident (note the motion of the marked and other beads relative to the pins). Photographs of the reconstructed image of the marked bead from the first and third holograms also appear in Fig. 2. The photographs of the bead were taken from the video monitor of the reconstruction system (the bead was actually 480 μm in diameter while the total field of view of the reconstructions is 1.9 × 2.9 mm within the object field). The reconstructed images of the bead appear as white outlines on a relatively dark background because the images are formed by the diffraction pattern from the periphery of the bead. The bright spot at the center of the images is caused by the focussing effect of the transparent glass bead. By seeking sharp images of the circular outline and the center spot, the axial position of the bead can be determined with reasonable accuracy (ca. 20 percent of the bead diameter for the present system).

Reconstructed holograms from the entire film strip were processed to obtain three-dimensional, time-dependent, trajectories of the glass beads. Two typical trajectories are illustrated in Fig. 3. Time is given as a parameter at points along the trajectories. The depth of the volume recorded, evidenced by the range of positions of the beads in z direction, is seen to be roughly 6 mm; however, axial coherence measurements of the laser indicate field depths up to 120 mm are feasible. Similarly, pulse rates up to 10 kHz, field diameters of 35 mm and film formats yielding up to 70 holograms on a film strip, can be accommodated by the present holocinematography system. Thus, the arrangement is capable of application to a variety of dispersed-phase events.

The authors gratefully acknowledge support provided by the Army Research Office under grant no. DAAL03-89-G-0004.

## References

1. J. D. Trolinger, "Particle Field Holography," Opt. Engrg. **14**, 383 (1975).

2. Y. J. Lee and J. H. Kim, "A Review of Holography Applications in Multiphase Flow Visualization Study," J. Fluids Engrg. **208**, 279 (1986).

3. K. J. Ebeling and W. Lauterhorn, "High Speed Holocinematography using Spatial Multiplexing for Image Separation," Opt. Commun. **21**, 67 (1977).

4. L. M. Weinstein, G. B. Beeler, and A. M. Linderman, "High-Speed Holocinematographic Velocimeter for Studying Flow Control Physics," AIAA Paper No. 85-0526.

5. J. D. Trolinger, "Laser Instrumentation for Flow Field Diagnostics," AGARD-AG-189, 1977, p. 72.

6. P. Hariharan, Optical Holography: Principles, Techniques and Applications (Cambridge University Press, New York, 1983), p. 175.

7. M. Lehman, Holography Technique and Practice (Focal Press Limited, London, 1970), p. 76.

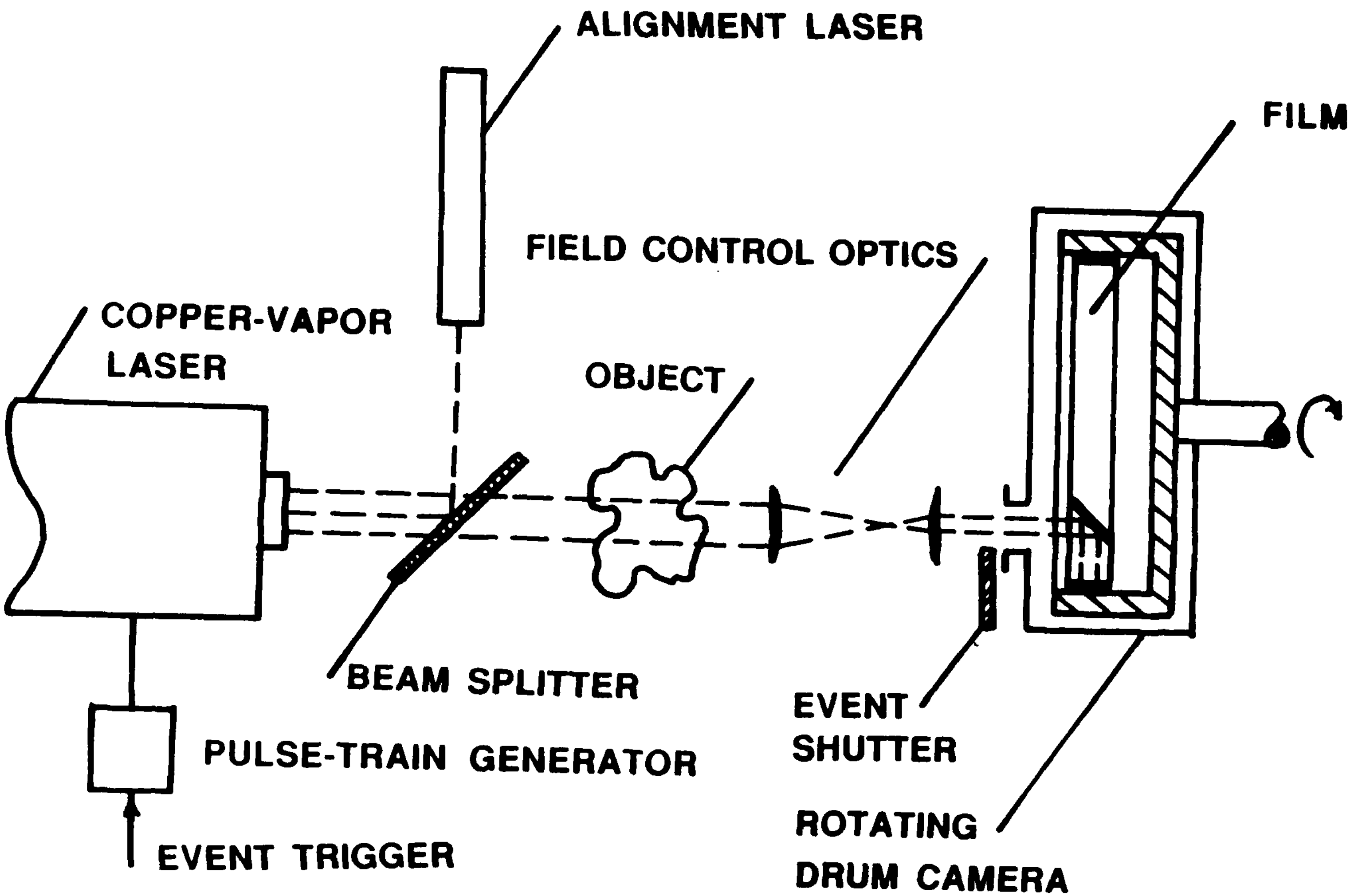


Fig. 1 In-line holocinematography recording system.

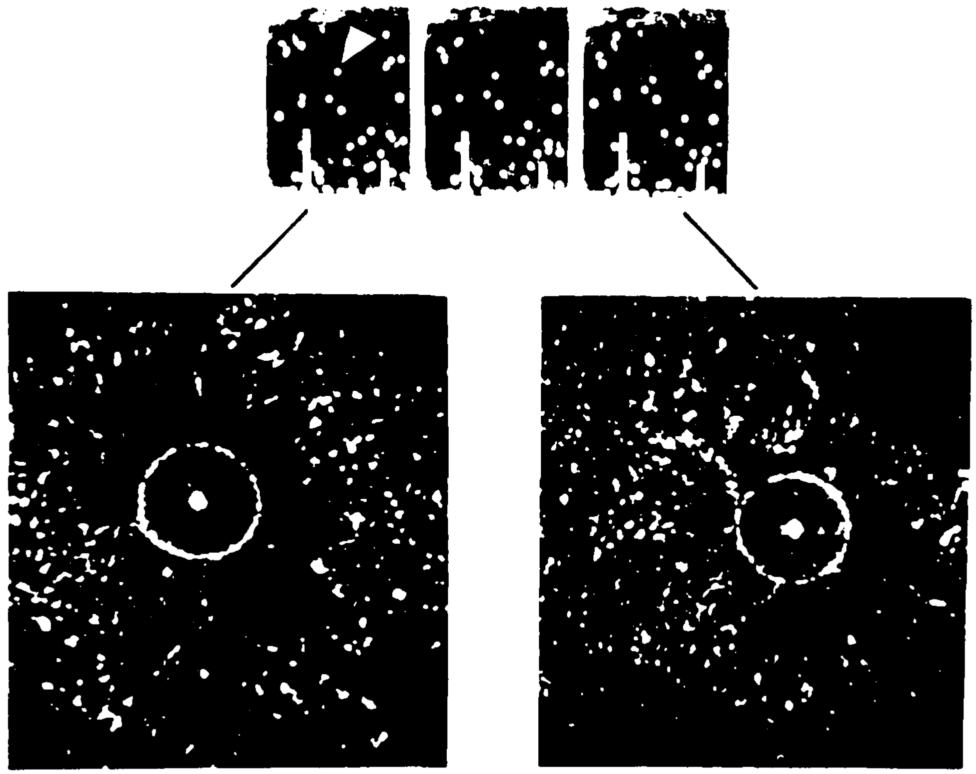

Fig. 2 Film strip of in-line holograms and corresponding reconstructed images of marked bead.

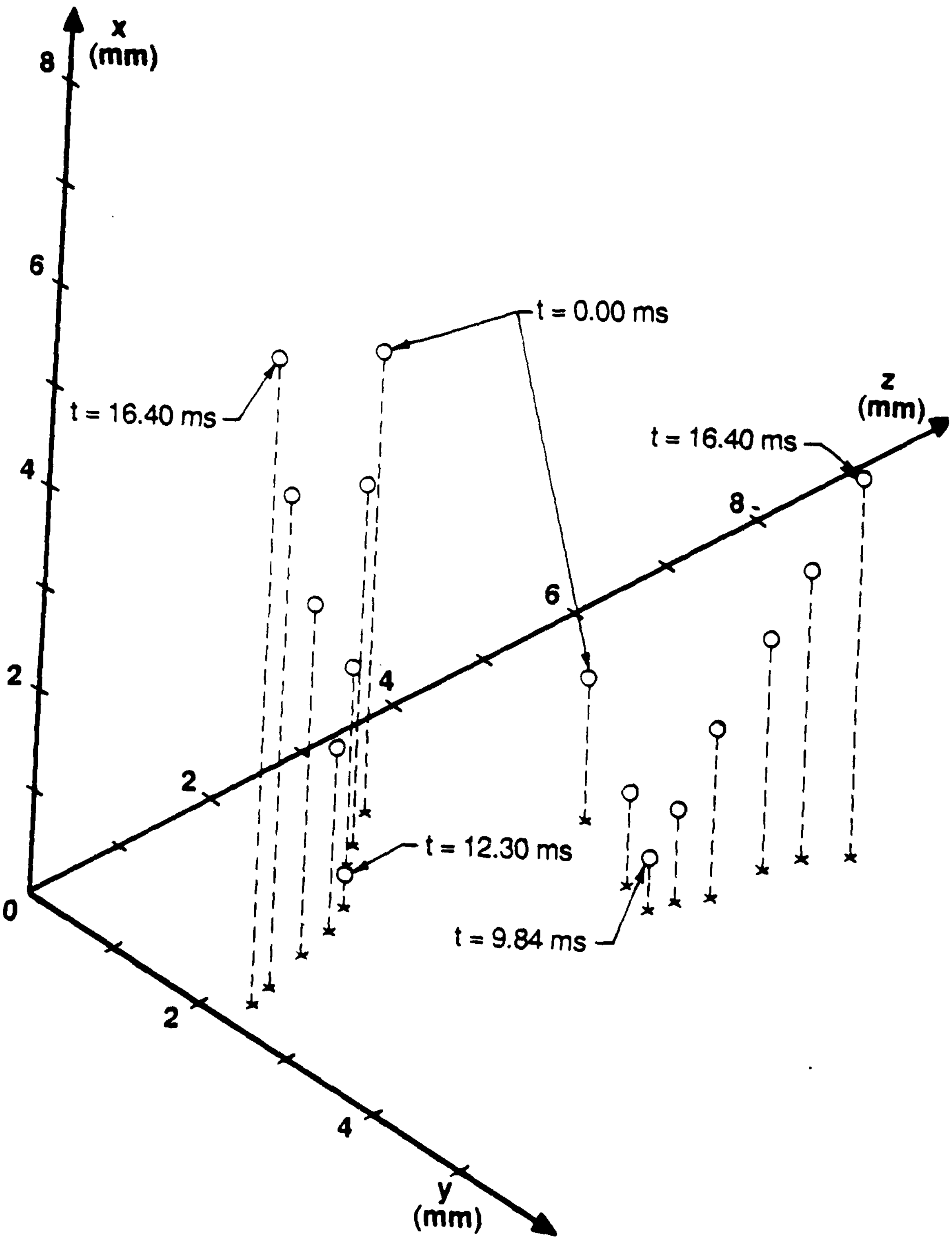


Fig. 3 Three-dimensional, time dependent tracks of two glass beads obtained from the hologram film strip.